THE NUCLEAR WEAPONS LATENCY VALUE OF THE JOINT

COMPREHENSIVE PLAN OF ACTION WITH THE ISLAMIC REPUBLIC OF IRAN

A Thesis

by

MARY AMELIA JOHANSEN

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	William Charlton
Committee Members,	Pavel Tsvetkov
	Matthew Fuhrmann
Head of Department,	Yassin Hassan

May 2016

Major Subject: Nuclear Engineering

ABSTRACT

The historic Joint Comprehensive Plan of Action (JCPOA) was implemented on January 16, 2016 between the Islamic Republic of Iran and the E3/EU+3. The JCPOA hopes to ensure that the nuclear program in Iran will exist solely for peaceful purposes. This agreement will end long-lasting and crippling sanctions enforced on Iran in exchange for inflexible reductions to the Iranian centrifuge enrichment program and assurances of the absence of efforts to develop, build, or acquire a nuclear weapon. Given Iran's past actions of nuclear hedging and pushing the boundaries of agreements, policymakers would benefit from a reliable method to judge the effectiveness of this agreement and how it should influence future policy. One method that can help inform policy decisions is with estimates of a state's Nuclear Weapon Latency. Nuclear Weapons Latency is defined as the time needed for a non-nuclear weapon state to develop a conventionally deliverable nuclear weapon.

Iran's Nuclear Weapon Latency was quantified with and without the JCPOA using the Nuclear Weapons Latency Computational Tool developed by D. Sweeney and W. Charlton at Texas A&M University. This MATLAB-based software focuses on the use of time-dependent proliferation pathway modeling using Petri Nets. The proliferation pathways used in this analysis include mining, milling, conversion, enrichment (gas centrifuge and atomic vapor laser isotope separation), reactor repair or construction, fuel fabrication, plutonium production, PUREX reprocessing, development of delivery systems, and weapon systems. A reference time was developed for each transition within

the pathway using the reported capacity or production of a facility when known or using the Pakistani nuclear program as a historic model if the characteristics for the Iranian facility are not known. The Petri Nets simulation provides an estimate of the distribution of likely time durations of a nuclear program until the first deliverable weapon is produced. The simulation can be analyzed to test for sensitivities due to the pathways and input parameters. This testing could be valuable in the development of policy and the identification of the key technologies that could most impact Iran's Nuclear Weapons Latency. The analysis performed here shows that the large reduction in the stockpile of nuclear material and enrichment capability caused a sizable increase in the Iranian Nuclear Weapons Latency.

DEDICATION

This thesis is dedicated to my children, Wesley and Virginia Johansen, without whom I would have never found the courage to begin this journey.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. William Charlton, for his insight, time, and expert guidance throughout this process, and my committee members, Dr. Tsvetkov and Dr. Fuhrmann, for their support throughout my time at Texas A&M. I would especially like to thank Dr. David Sweeney for his time, understanding, and the use of his Nuclear Weapons Latency Tool, which is the basis for this work. I would also like to thank Dr. Sunil Chirayath for his expertise, knowledge, and time.

NOMENCLATURE

AVLIS	Atomic Vapor Laser Isotope Separation
E3/EU+3	China, France, Germany, the Russian Federation, the United Kingdom, and the United States, with the High Representative of the European Union for Foreign Affairs and Security Policy
GDP	Gross Domestic Product
FFL	Fuel Fabrication Laboratory
FPFP	Fuel Plate Fabrication Plant
HEU	High-Enriched Uranium
HWRR	Heavy-Water Research Reactor
IAEA	International Atomic Energy Agency
JCPOA	Joint Comprehensive Plan of Action
KANUPP	Karachi Nuclear Power Plant
KCP-1	Khushab Chemical Plant-1
LEU	Low-Enriched Uranium
LWR	Light Water Reactor
MOX	Mixed Oxide Fuel
NFEP	Natanz Fuel Enrichment Plant
NPFEP	Natanz Pilot Fuel Enrichment Plant
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
PUREX	Plutonium Uranium Redox Extraction

PWR	Pressurized Water Reactor
R&D	Research and Development
SNM	Special Nuclear Material
SWU	Separative Work Unit
TNRC	Tehran Nuclear Research Center
TRR	Tehran Research Reactor
UCF	Uranium Conversion Facility
WGPu	Weapon-Grade Plutonium
WGU	Weapon-Grade Uranium
ZPP	Zirconium Production Plant

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Page

1. INTRODUCTION

1.1 Background

The historic Joint Comprehensive Plan of Action (JCPOA), which was implemented on January 16, 2016, between the Islamic Republic of Iran and the E3/EU+3 (China, France, Germany, the Russian Federation, the United Kingdom, and the United States, with the High Representative of the European Union for Foreign Affairs and Security Policy) hopes to ensure that the nuclear program in Iran will exist solely for peaceful purposes.[1] This agreement will end long-lasting and crippling sanctions enforced on Iran in exchange for inflexible reductions to the Iranian centrifuge enrichment program; assurances of the absence of effort to develop, build, or acquire a nuclear weapon; the ratification of Additional Protocols; as well as other actions which must be taken by Iran and verified by the International Atomic Energy Agency (IAEA).[2] After the ratification of Additional Protocols, the IAEA will be granted the ability to conduct additional safeguarding measures within the state and obtain complete knowledge of the facilities within Iran which are related to the nuclear fuel cycle, including those with non-nuclear materials.[3] These additional measures include the ability to conduct wide area sampling to look for undeclared activity and the issuance of multi-entry visas for inspectors. These new inspection practices could help to build trust and verify the current activities within Iran.

This agreement marks an important change in the tone of the diplomatic relations with Iran. The ratcheting down of the relations between the United States and Iran may allow for a more productive dialogue, not only between the United States and Iran, but also with Iran's neighbors which have felt alienated and threatened by the possibility of a nuclear Iran. This might have the effect of slowing proliferation in the region.[4]

Others in the international community argue however that since signing the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) in 1970 and agreeing not to develop nuclear weapons, the Iranians have continually pushed the boundaries and, in fact, acted in a way which is in opposition to the treaty; never truly acting in good faith.[5]

This work will examine Iran's proliferation pathways and determine the impact of the JCPOA will have on the amount of time expected for Iran to produce a conventionally deliverable nuclear weapon if it chose to do so (which we refer to as the Nuclear Weapons Latency). It is generally agreed that the longer it takes for a state to proliferate, the less likely they are to do so and the less threatening they are to their neighbors. Thus, we expect the Nuclear Weapons Latency to provide a strong indicator of the proliferation potential for a state and of the destabilizing potential for a state proliferation program. For the Iranian program, we expect that the JCPOA will increase the Nuclear Weapons Latency, but in this work, we will quantify that impact under both covert and breakout scenarios.

1.2 Nuclear Weapons Programs

Nuclear weapons programs involve the acquisition of Special Nuclear Material (SNM), the design and fabrication of the nuclear explosive, and the development of a suitable delivery system. SNM primarily consists of highly-enriched uranium (HEU) and plutonium (containing less than 80% ^{238}Pu). HEU is uranium enriched to greater than 20% by mass in the isotope ^{235}U. SNM does not occur in nature and must be produced using highly specialized facilities. A nuclear weapons program typically uses materials of a higher quality, sometimes referred to as weapons-grade. There is not a specific technical definition for weapons-grade materials, but weapons-grade uranium (WGU) typically is uranium with an enrichment of around 90% in the isotope ^{235}U. Weapons-grade plutonium (WGPu) is plutonium with a quantity of ^{240}Pu of around 6%. A significant amount of effort is used to generate these materials and this often can be the lengthiest portion of the program. However, it can be important to consider the weaponization activities and delivery system activities as well when fully characterizing a nuclear weapons program.[6]

1.3 Nuclear Weapons Latency Tool

The time needed for a non-nuclear weapon state to develop a conventionally deliverable nuclear weapon is referred to as the Nuclear Weapons Latency. An accurate assessment of this time is a critical piece of information for policymakers. The software used for this quantitative measurement was developed by D. Sweeney and W. Charlton at Texas A&M University[7] and makes three basic assumptions:

1. The decision to proliferate has been made
2. The times to complete individual tasks are able to be estimated
3. The pathways to a weapon are known

This software focuses on the use of time-dependent proliferation pathways to simulate a state's proliferation using Petri Nets.[7] Petri Nets are used to model complicated systems using transitions (symbolized with rectangles) and places (symbolized with circles). Transitions describe an action that is being undertaken. Places denote work that has been done and show your location along a proliferation pathway. Places connect to transitions and vice versa using directional arcs. Tokens or markers within places denote your location along the path. When the correct number of tokens are within a place, the transition is enabled. The transition will fire, and after a certain amount of time has passed the tokens are sent downstream to the next place. The time-dependent Petri Nets used in this simulation are stochastically timed using a user defined probability density function that is randomly sampled each time the transition is enabled. The number of tokens needed for a particular transition to fire and the number of tokens disseminated to the places immediately downstream is a function of the arcs connecting the place to the transition and from the transition to the following place, or places.

The Nuclear Weapons Latency Tool uses the MATLAB programing language to analyze the time-dependent Petri Nets to arrive at an estimate of a state's Nuclear Weapon Latency time.[8] Petri Nets are built using Microsoft Visio and the matrices required as inputs are created using a macro within the Visio program. The entire network of paths which lead to proliferation are available to be analyzed by the tool; however, preferred paths can be established by the user. These preferred paths are used to test sensitivities within the network and identify pivotal paths. Identifying these key pathways could be important information used by policy makers when assessing their interactions with a state.

2. THE IRANIAN NUCLEAR COMPLEX

To determine the proliferation capacity of Iran, the speed with which material moves through the system, and in order to build the proliferation pathways needed to utilize the Nuclear Weapons Latency Tool, the operating fuel cycle facilities, stockpiles of SNM, and research and development (R&D) facilities in Iran were studied and quantified. This examination was conducted using documents and reports resulting from inspections of Iran by the IAEA, satellite imagery, and declarations made by Iran, both historically and contemporarily. The results of this examination were used to determine the transition timing for the movement of material through the system.

The Iranian nuclear complex includes mining, milling, and conversion of natural uranium for (1) production of natural uranium fuel for the IR-40 heavy-water reactor under construction at Arak or (2) enrichment at the Natanz Fuel Enrichment Plant to 3.67% enriched uranium hexafluoride. This 3.67% enriched material would then be (a) converted into power reactor fuel for a nuclear power plant or (b) continued to be enriched to either 19.75% for research reactor fuel for the Tehran Research Reactor (TRR) or to greater than 70% for weapons manufacturing. Iran also possesses a number of R&D facilities. Each of the facilities in the Iranian nuclear complex is discussed below including quantification of the capacity of those facilities.

2.1 Nuclear Fuel Cycle Facilities

The types of nuclear activities that were included in this analysis included uranium mining, milling, enrichment [specifically gaseous centrifuge enrichment and atomic vapor laser isotope separation (AVLIS)] nuclear reactors (building facilities, fuel irradiation, and fuel storage before reprocessing), fuel fabrication [natural uranium fuel, low-enriched uranium (LEU) fuel, and production of cladding], and Plutonium Uranium Redox Extraction (PUREX).

2.1.1 Uranium Mines

The major uranium mining facilities in Iran are the Saghand and Gachin mines. The Gachin mine is an open-pit mine which produces approximately 21 tons of uranium per year and has an ore grade of 0.05%. The Saghand mine is an underground mine which produces approximately 50 tons of uranium per year and has an ore grade of 0.20%.[9-11] Uranium ore grades vary by geographic location, but generally the content of uranium near uranium mines ranges from 0.03% to 24%.[12] The low quantity of the uranium ore found in this region is a major obstacle for Iran's nuclear program.

2.1.2 Uranium Milling Facilities

The two major uranium milling facilities at Ardakan and Gachin are responsible for taking the uranium ore from the mines and converting it into yellowcake, U_3O_8. The larger of the two mills, Ardakan, processes approximately 50 tons of uranium per year, matching the capacity of the Saghand mine. The second mill, Gachin, matches the output of the Gachin mine, approximately 21 tons of uranium per year.[13]

2.1.3 Uranium Conversion Facilities

There is one main conversion facility in Iran, the Esfahan Uranium Conversion Facility (UCF). This facility converts the yellowcake, or U_3O_8, into uranium hexafluoride (UF_6) gas to be used in the gas centrifuge enrichment facilities and into uranium dioxide (UO_2) and natural uranium metal for use as reactor fuel.[14] UCF produces approximately 140 tons of UF_6 per year.

2.1.4 Gaseous Centrifuge Enrichment Facilities

2.1.4.1 Gaseous Centrifuge Enrichment Prior to JCPOA

While the Iranians have experimented with several advanced centrifuges, their current enrichment program utilizes two types of gas centrifuges: the IR-1 and the IR-

2m.[15] Each IR-1 centrifuge has a separative capacity of 0.9 SWU (Separative Work Unit) per year. The more advanced, but unreliable, IR-2m centrifuge has a separation factor of between 3 and 5 SWU per year.

The largest gas centrifuge enrichment facility in Iran is the Natanz Fuel Enrichment Plant (NFEP). It contains 9,494 active IR-1 centrifuges and 6,250 IR-1 centrifuges which are idle but available to enrich.[15, 16] Also located at the NFEP are 1,008 active IR-2m centrifuges and an additional 2,088 IR-2m centrifuges which are in the process of being installed.[17, 18] The NFEP produces 3.67% enriched uranium hexafluoride product. Overall, the NFEP has an active capacity of 11,568-13,584 SWU per year with an additional 11,889-16,050 SWU per year idle.

The Natanz Pilot Fuel Enrichment Plant (NPFEP) uses 328 IR-1 centrifuges to produce 19.75% enriched uranium, presumably for the TRR, using 3.67% enriched uranium feed from the NFEP. Thus, the NPFEP has a total capacity of 295 SWU per year.

The Fordow Fuel Enrichment Plant (FFEP) is also an IR-1 facility. It contains 696 active gaseous centrifuges and 2,014 centrifuges which are idle but available to enrich.[19] Thus, the FFEP has an active capacity of 626 SWU per year with an additional 1812 SWU per year idle. The FFEP uses 3.67% enriched uranium feed to produce 19.75% enriched uranium product. It was also suspected that the FFEP had originally been designed to produce WGU at or near 90% enriched.

2.1.4.2 Gaseous Centrifuge Enrichment Post-JCPOA

The reduction of installed centrifuges under the JCPOA is impactful. After the implementation of the JCPOA, the number of IR-1 centrifuges at the Natanz facility will be reduced from 15,744 to 5,060. Additionally, the IR-2m centrifuges, superfluous IR-1 centrifuges, and replacement parts will be stored under constant monitoring by the IAEA.[1] This reduces the Iranian gaseous centrifuge capacity by over 80% to 4,554 SWU per year.

2.1.5 AVLIS

From the 1970's until 2003, Iran conducted research into AVLIS at a secret site known as Lashkar Ab'ad.[20] The facility, before dismantling, would have been capable of producing 5 kg of 3.5%-7% enrichment by the end of the first year, and if fully implemented might have been capable of producing minute quantities of HEU.[21, 22] AVLIS has many advantages to a centrifuge facility which make it ideal as a covert facility under the JCPOA. These advantages include having a small footprint and a small heat signature. Additionally, this past work has provided experience into the AVLIS process.

2.1.6 Nuclear Reactors

2.1.6.1 Arak IR-40 Heavy-Water Research Reactor

The IR-40 is a 40 MW Heavy-Water Research Reactor (HWRR) which is still under construction. Iran has reported that this facility is 68% complete. This reactor is of particular concern because when functioning optimally it would be capable of producing 9 kg of WGPu annually.[23, 24] The JCPOA calls for the Arak reactor to be redesigned to operate using fuel enriched to 3.67%, and without producing WGPu. The calandria tank will be removed from the reactor and rendered inoperable by filling it with concrete. Additionally, all spent fuel will be shipped out of Iran for the life of the reactor.[1]

2.1.6.2 Bushehr Pressurized Water Reactor

The Bushehr Pressurized Water Reactor (PWR) is a 1000 MWe reactor. Russia supplies the fuel for this reactor and is responsible for the removal of spent fuel when it is safe for transport.[25, 26] This facility has been bombed, suffered delays because of pump damage, and is built on a fault line. However, even due to all of these issues, the reactor is a fairly typical power reactor and is generally considered to not be a proliferation concern.

2.1.6.3 Tehran Research Reactor

The TRR is a 5 MWth Light-Water Reactor (LWR). This reactor, along with its HEU fuel, was originally supplied to Iran by the United States.[27] In 1987, Argentina adapted the reactor to utilize fuel enriched to only just under 20% and sold 161 kg of fuel to Iran.[28] The JCPOA calls for Iran to utilize all the uranium oxide which is enriched between 5% and 20% to fabricate fuel plates for the TRR and for all spent fuel to be removed from Iran.[1]

2.1.7 Fuel Fabrication

The fuel fabrication facilities within Iran are limited to the Fuel Fabrication Laboratory (FFL), the Fuel Plate Fabrication Plant (FPFP), and the Zirconium Production Plant (ZPP) located near Esfahan.[29] The IAEA reported in 2004 that the FFL has only a limited fuel pellet production capability.[30] The FPFP produces the natural uranium fuel for the IR-40 HWRR and is capable of producing the fuel for the Bushehr PWR, but the JCPOA mandates that this fuel be supplied by and then returned to Russia after irradiation.[31] ZPP produces the cladding used to encase the fuel. The cladding helps to contain the fission products produced within the fuel during irradiation and ensures they do not leak into the environment. ZPP, when completed, will be able to produce 10 tons of zirconium tubing per year for nuclear fuel cladding. The operational status of this facility is unclear.[32]

2.1.8 Reprocessing Facilities

Reprocessing refers to the extraction of actinides of interest, generally uranium and plutonium, from spent fuel. There is no evidence to suggest that Iran operates any reprocessing facilities large enough to be capable of reprocessing spent fuel.[23] Only small, research-like facilities (hot cells) are known to exist in both the Arak Nuclear Complex and the Tehran Nuclear Research Center (TNRC). A large facility would be needed to produce enough WGPu for a weapon. However, the JCPOA expressly forbids even the R&D of reprocessing techniques as well as the import of the equipment needed.

The typical spent fuel reprocessing method used today is some variant of the PUREX process. The PUREX process has been in use since the 1950's and has many proliferation concerns. The process begins with the chopping of the spent fuel. The chopped fuel is then dissolved in nitric acid, separating the cladding from the fuel.[33] The dissolved fuel, which contains the uranium and plutonium, enters into a solvent extraction process. The end result is uranium (potentially in the form of UO_2 or even UF_6, which is suitable for gaseous enrichment), and PuO_2, which can be converted into plutonium metal for an implosion weapon. The footprint of a PUREX facility is large and the equipment needed is specialized and tightly controlled. Equipment such as hot cells, remote manipulators, and large glove boxes are not allowed under the JCPOA.[1]

2.1.9 Heavy-Water Production Facilities

Heavy water is water which contains deuterium (an isotope of hydrogen whose nucleus is comprised of both a neutron and a proton). Heavy water has a much smaller neutron absorption cross-section than ordinary light water, which allows it to be used as a moderator in natural-uranium fueled reactors. Because of the proliferation concerns surrounding natural-uranium fueled reactors, the JCPOA puts strict controls and limits on the amount of heavy water that can be produced at the heavy-water production plant near Khondab.[1] The JCPOA limits the Iranian heavy-water inventory and production to 130 metric tons of nuclear-grade heavy water prior to the commissioning of the Arak Research Reactor, and 90 metric tons afterward.

2.2 SNM Stockpiles

Based on data in the August 2013 IAEA Safeguards Report, the Iranian stockpile consisted of 6,774 kg of 3.5% enriched UF_6, 186 kg of near 20% enriched UF_6, and about 130 kg of near 20% enriched UO_2.[15, 17, 18] After the implementation of the JCPOA, Iran is required to reduce this stockpile to a maximum of 300 kg of UF_6 enriched to no more than 3.67%.[1]

2.3 Research and Development Facilities

Iran has several R&D facilities studying nuclear weapons development. These facilities include:

- Jabr Ibn Hayan Multipurpose Laboratories
- Parchin Military Complex
- Physics Research Center
- TNRC
- Ministry of Defense, Armed Forces and Logistics

The research conducted in these facilities is thought to include missile technology, gun-type weapon design, and implosion weapon technology and design.[28, 34-39]

3. NUCLEAR WEAPONS LATENCY MODEL FOR IRAN

Using the known Iranian nuclear capabilities and the Nuclear Weapons Latency Tool, a set of models were constructed to assess Iranian Nuclear Weapons Latency both without and with the JCPOA in force. In this chapter, the model used for these calculations is described.

3.1 Transition Times

A historical model was used to accurately estimate the time needed to complete each transition (for those not currently occurring in Iran). A set of characteristics were considered in order to choose an appropriate historical model for Iran. The state should (a) not be a nuclear weapon state under the NPT, (b) possess nuclear weapons (at this time or historically), (c) possess reprocessing capabilities, and (d) be statistically similar to Iran [in terms of population, land area, and Gross Domestic Product (GDP)]. States that meet the requirements (a), (b), and (c) include:

- Israel
- Pakistan
- India
- Democratic People's Republic of Korea (DPRK)

The statistical data for each of these states was collected and compared to determine the most appropriate historical model for Iran. The results from the statistical comparison for each of these states can be seen in Table 1. Israel and the DPRK are clearly much smaller states than Iran in terms of all of the statistics considered. In contrast, India is clearly a much larger state than Iran in terms of the statistics considered. Pakistan appears to be the most suitable historical model based on its relative similarity in land area and GDP and somewhat similar populations.

Table 1: Comparison of Israel, India, Pakistan, and DPRK to Iran to Determine Their Suitability as Historic Models.

Country	**Population**		**Land Area**		**GDP**	
	Population (million)	Percent difference from Iran	Area (mi^2)	Percent difference from Iran	GDP (trillion)	Percent Difference from Iran
Iran	78	n/a	636,372	n/a	1.015	n/a
Israel	8	-90%	8,019	-99%	0.28	-72%
India	1,276	1536%	1,269,346	99%	8.03	691%
Pakistan	199	155%	340,509	-46%	0.93	-8%
DPRK	25	-68%	46,528	-93%	0.40	-61%

3.2 Building of Proliferation Pathways

Proliferation pathways were constructed using Microsoft Visio to illustrate the movement of material and advancement of capabilities pertinent to proliferation. These pathways were constructed to reflect as accurately as possible the Iranian nuclear program as described in Section 2.

3.2.1 Types of Pathways

Pathways can be classified as either material or facility paths based on the actions conducted on that path. Facility paths are associated with the building of a facility, or technological advancements, such as the constructing of a reactor or AVLIS facility. Figure 1 shows the facility pathways which represents the construction and operation of a reprocessing facility, there are two possible materials that could result from these paths, UO_2 and PuO_2. Tokens within places on facility paths represent a constructed facility or success in a technological advancement.

Material paths involve the changing of the physical, elemental, or isotopic form of a material (such as enrichment or mining). Figure 2 shows a simplified material pathway beginning with mining and branching off to show the abridged paths to a weapon. Tokens on uranium pathways represent 1 kg of ^{235}U, and tokens representing possession of plutonium represent approximately 4.5 kg of plutonium, half of the Pu produced annually from the Arak reactor.

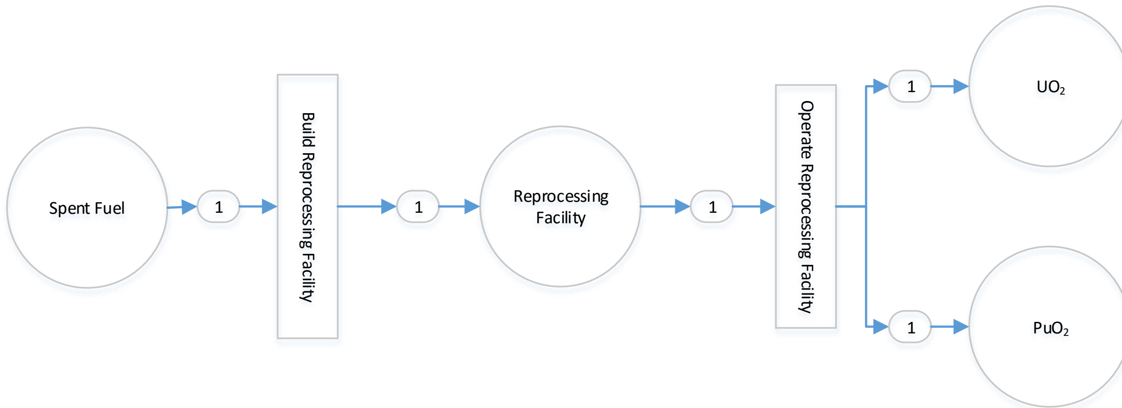

Figure 1: Excerpt from Simplified Facility Pathway Showing the Building and Use of a Reprocessing Facility. The first place, on the far left, symbolizes the possession of spent fuel. After a token is in this place, it will enable the transition that symbolizes the construction of a reprocessing facility. Once the stochastically determined time has elapsed the token will move to show the completion and readiness of this facility. Then the second transition, which symbolizes the reprocessing of the fuel, will be enabled and after the allotted time one of the places, symbolizing the products of reprocessing, will gain a token.

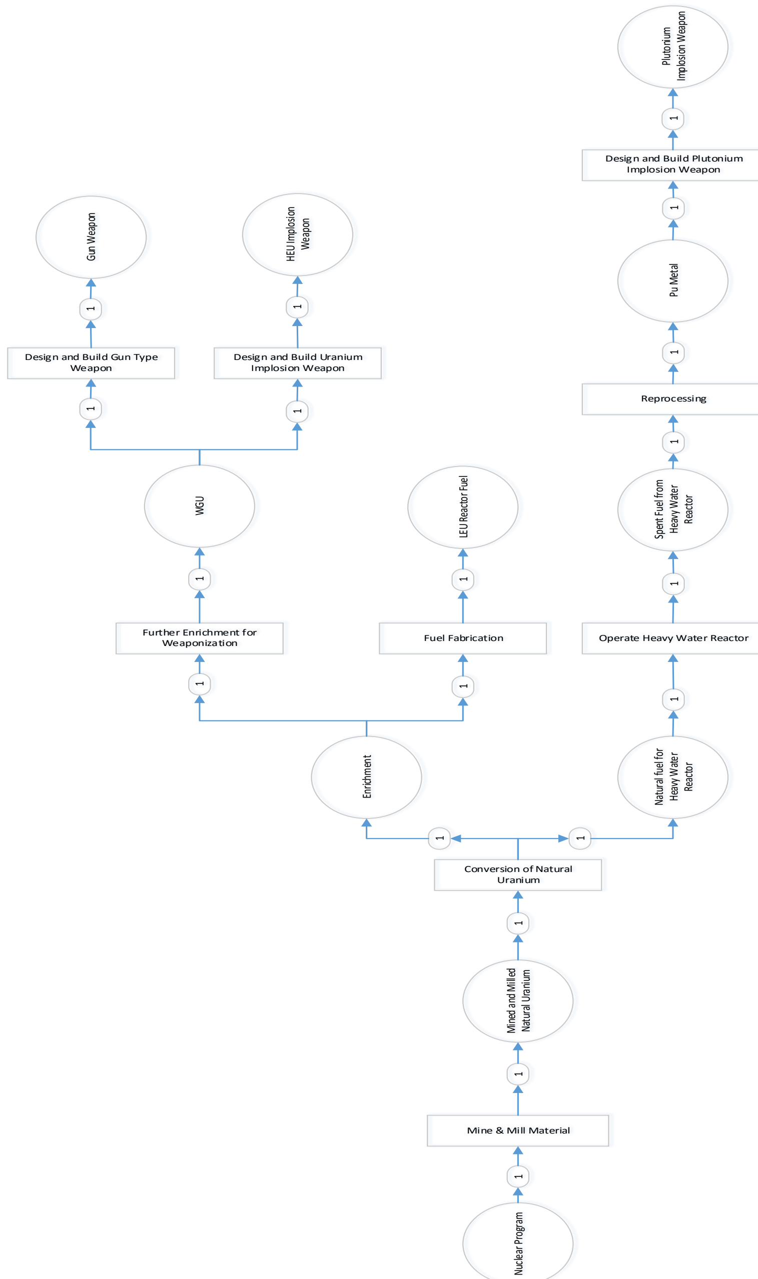

Figure 2: Simplified Material Pathway Showing the Flow of Nuclear Material from Mining to Weaponization. This material pathway begins at the bottom of the figure with the mining and milling of uranium. After the conversion the uranium can either go to the enrichment facility or to a fuel fabrication facility to produce fuel for a HWR. If the uranium follows the enrichment path it can either end in Weaponization (gun-type or HEU implosion) or fuel for a reactor. If the uranium went to fuel for a HWR after conversion the material pathway will continue through reprocessing and a plutonium implosion-type weapon.

3.2.2 Specific Characteristics of Iranian Pathways Model

While much is available in the open literature about the Iranian nuclear program, we do not have complete information about all aspects of the facilities. Thus, a number of assumptions were made in order to allow for a complete estimation of the Iranian Nuclear Weapons Latency. For facility transition times that were not openly available, we used the similar facility in Pakistan as a model. The facilities for which assumptions were made beyond that information available in Chapter 2 are given below. The known SNM stockpiles for Iran were used to place markers simulating the starting place for proliferation.

3.2.2.1 AVLIS

The full scale AVLIS facility modeled is capable of enriching natural uranium to 5%. The effort to enrich material to 5% represents 70% of the required energy to enrich to 93%. The transition timing was modeled using the New Labs facility in Pakistan.[41] The New Labs facility is a full scale technical facility, similar to the size and specialization of an AVLIS facility.

3.2.2.2 Arak IR-40 HWRR and other HWRR's

In the model for the IR-40, the completion time of the construction for the IR-40 HWRR was assumed to be 32% of the time it took Pakistan to construct Karachi Nuclear Power Plant (KANUPP) in Pakistan.[41] KANUPP is a 90 MWe pressurized HWR operated by the Pakistan Atomic Energy Commission. The construction of this reactor started on August 1, 1966 and became critical on August 1971.[42] This reactor will serve as a historical model when a HWR is constructed within a proliferation pathway.

3.2.2.3 Reprocessing

Because of the absence of any such facility in Iran, the modeling of this facility will be based on the New Labs in Pakistan.[7, 41]

3.2.2.4 Heavy Water

When modeled for plutonium production with the JCPOA in force, the construction transition time of a heavy-water production facility will make use of the historic model of Khushab Chemical Plant-1 (KCP-1) heavy-water production plant in Pakistan.[7, 41]

3.2.2.5 Delivery Systems

The Islamic Republic of Iran has numerous programs for the development of ballistic and cruise missiles and long-range artillery rockets, and currently possesses the largest number of deployed missiles in the Middle East.[43] The Iranian ballistic missile program began in the early 1980's and currently claims to have developed five liquid-propellant ballistic missiles and a solid-propellant missile. The Iranian cruise missile program began in 2001, and in 2012 they announced that they had developed fourteen different cruise missiles.[44] When modeling delivery system technology, it will be assumed that the conventional delivery system exists, but must be retrofitted to accommodate a nuclear component.

3.2.2.6 Weapon Designs and Components

There are several research sites in Iran that are known to have carried out research into components and weapon design. It was found in the 1990's that the TNRC Laboratories produced polonium-210 (material used in a beryllium-polonium neutron initiator) through the irradiation of bismuth targets.[28] Additionally, The large Parchin complex is dedicated to research, development, and production of ammunition, rockets, and high explosives.[34] The IAEA determined that the testing facilities that exist at Parchin include those that could be used for (a) a test of the spherical symmetry of the initiation of the high explosive component of a nuclear warhead, (b) tests to ascertain the symmetry of an imploding hemispherical shell of high explosive, and (c) a test of a uranium deuteride neutron initiator.[37] Because of these activities, when modeling weaponization the assumption is made that the production of components (i.e. initiators and tampers) and that untested weapon designs have been completed.

4. PROLIFERATION PATHWAYS WITHOUT THE JCPOA

Four pathways were modeled using the known capabilities, facilities, and SNM present in Iran.[15] The assumptions made when constructing these pathways included:

- Facilities are operating at 100% capacity
- Untested weapon designs existed
- Arak HWRR is 68% completed

Three different types of weapons were modeled within the simulations: HEU gun-type weapon, HEU implosion-type weapon, and WGPu implosion-type weapon. The plutonium pathways included both the reprocessing of spent fuel as well as the illicit purchase of WGPu metal.

4.1 Gun-Type Weaponization Pathway

The material pathways necessary for a gun-type weapon include the mining, milling, conversion, and enrichment of uranium. The facility pathways involve the use of existing enrichment and conversion facilities, the reconfiguration of the enrichment hall to facilitate the production of WGU, R&D of delivery systems, and the testing of gun-type weapon designs. The transitions times used for the entire proliferation pathway can be seen in Table 2.

Table 2: List of Transition Times Used for the Gun-Type Proliferation Pathway Outside of the JCPOA. The days listed are the transition times used as reference times for each task. The days for material pathways (mining, milling, and conversion) are times for 1 kg of ^{235}U to pass through that stage. While enrichment times are inclusive for the material needed for the gun-type weapon. The construction of the enrichment and metal conversion facilities is 1 day in this case because they are existing. This is also the case for the testing of delivery systems and the production of untested weapons designs.

Number	Transitions	Days
1	Yellowcake from Gachin	1
2	Yellowcake from Ardakan	1
3	Produce yellowcake in Gachin mill	3
4	Mine Gachin	2
5	Produce yellowcake in Ardakan Production Plant	2
6	Convert U3O8 to UF6 for use in centrifuge facility	1
7	Mine Saghand	1
8	Operate enrichment facilities	34
9	Build enrichment facilities (existing facility)	1
10	Operate WGU enrichment facilities	7
11	Reconfigure LEU Plants for WGU production	30
12	Operate HEU Metal Conversion Facility	84
13	Build U Metal Conversion Facility (existing facility)	1
14	Retrofit Delivery System for nuclear payload	60
15	Test Delivery/Missile Systems (existing technology)	1
16	Possess Deliverable U Gun Weapon	1
17	Produce U Gun Explosive	180
18	Design U Gun Explosive (existing weapon design)	1
19	Initiate Weapons R&D	1

4.2 HEU Implosion-Type Weaponization Pathway

The material pathways necessary for a HEU implosion-type weapon include the mining, milling, conversion, and enrichment of uranium. The facility pathways involve the use of existing enrichment and conversion facilities, reconfiguration of the enrichment hall to facilitate the production of WGU, R&D of delivery systems, and the hot and cold testing of implosion weapon designs. The times used for hot and cold tests and test preparation are derived from the historical example of the Pakistani nuclear program.[7, 41] The transitions times used for the entire proliferation pathway can be seen in Table 3.

4.3 Plutonium Implosion-Type Weaponization Produced with Reprocessing Pathway

The material pathways necessary for a plutonium implosion-type weapon include the mining, milling, conversion, fuel fabrication, fuel irradiation, and spent fuel reprocessing. The facility pathways involve the completion of the Arak HWRR, R&D of delivery systems, and the hot and cold testing of implosion weapon designs. The times used for hot and cold tests, test preparation, completion time of the reactor, and construction of reprocessing plant are derived from the historical example of the Pakistani nuclear program.[7, 41] The transitions times used for the entire proliferation pathway can be seen in Table 4.

Table 3: List of Transition Times Used for the HEU Implosion-Type Weapon Proliferation Pathway Outside of the JCPOA. The days listed are the transition times used as reference times for each task. The days for material pathways (mining, milling, and conversion) are times for 1 kg of ^{235}U to pass through that stage. While enrichment times are inclusive for the material needed for the HEU implosion-type weapon. The construction of the enrichment and metal conversion facilities is 1 day in this case because they are existing. This is also the case for the testing of delivery systems and the production of untested weapons designs. The time to build the testing facilities and conduct testing were extracted from the Pakistani historic model.

Number	Transitions	Days
1	Retrofit delivery system for nuclear payload	60
2	Test Delivery/Missile Systems (existing technology)	1
3	Possess Deliverable HEU Weapon	1
4	Produce HEU Imp Explosive	180
5	Subcritical (cold) Test HEU Design with Nat U	192
6	Nuclear Test HEU Nuclear Explosive	192
7	Prepare HEU Subcritical (cold) Testing Facility	4434
8	Prepare HEU Nuclear Explosive Testing Facility	2202
9	Design HEU Implosion Weapon (existing weapon design)	1
10	Initiate Weapons R&D	1
11	Operate 2nd enrichment facilities	33
12	Operate enrichment facilities	158
13	Build enrichment facilities (existing facility)	1
14	Operate WGU facilities	12
15	Reconfigure LEU Plants for WGU production	30
16	Operate HEU Metal Conversion Facility	84
17	Build Uranium Metal Conversion Facility (existing facility)	1
18	Yellowcake from Gachin converted to UF6	1
19	Yellowcake from Ardakan converted into UF6	1

Table 3: Continued

Number	Transition	Days
20	Produce yellowcake in Gachin mill	3
21	Mine Gachin	2
22	Produce yellowcake in Ardakan Production plant	2
23	Convert U3O8 to UF6 for use in centrifuge facility	1
24	Mine Saghand	1

Table 4: List of Transition Times Used for the Plutonium Implosion-Type Weapon with Reprocessing Proliferation Pathway Outside of the JCPOA. The days listed are the transition times used as reference times for each task. The days for material pathways (mining, milling, and conversion) are times for 1 kg of ^{235}U to pass through that stage. The investigation of fuel needs for reactor is 1 day in this case because they are known. This is also the case for the testing of delivery systems and the production of untested weapons designs. The time required to build the reprocessing facility, to complete the HWR, the time required to reprocess the fuel, to construct testing facilities, to conduct weapons testing, and to produce the heavy water needed for the reactor are taken from the Pakistani historic model.

Number	Transitions	Days
1	Retrofit for nuclear payload	60
2	Test Delivery/Missile Systems (existing technology)	1
3	Possess Deliverable Pu Weapon	1
4	Produce Pu Imp Explosive	180
5	Subcritical (cold) Test Pu Design with Nat U	192
6	Nuclear Test Pu Nuclear Explosive	192
7	Prepare Pu Subcritical (cold) Testing Facility	4434

Table 4: Continued

Number	Transition	Days
8	Prepare Pu Nuclear Explosive Testing Facility	2202
9	Design Pu Implosion Weapon (existing weapon design)	1
10	Initiate Weapons R&D	1
11	Build Reprocessing Facility	2555
12	Reprocess at facility	165
13	Cool Fuel	200
14	Operate Arak Reactor	365
15	Produce heavy water for Arak Reactor	365
16	Complete Arak Reactor	1402
17	Investigate Needs for Arak reactor completion	30
18	Operate Nat Metal Conversion Facility	90
19	Yellowcake covertly converted into UO2 for natural uranium fuel	2
20	Yellowcake from Gachin converted to UF6	1
21	Yellowcake from Ardakan converted into UF6	1
22	Produce yellowcake in Gachin mill	3
23	Mine Gachin	2
24	Produce yellowcake in Ardakan Production plant	2
25	Mine Saghand	1
26	Possess fuel for Arak heavy-water reactor	1
27	Operate Esfahan Fuel Fabrication Facility	180
28	Investigate Fuel Fabrication Facilities and options	1

4.4 Plutonium Implosion-Type Weaponization Produced with Illicit Plutonium Metal Purchase

There are no material pathways necessary for a plutonium implosion-type weapon built with acquired plutonium metal. The facility pathways involve the hot and cold testing of implosion weapon designs, purchase of the plutonium metal, and delivery systems. The times used for hot and cold tests and test preparation are derived from the historical example of the Pakistani nuclear program.[7, 41] The transitions times used for the entire proliferation pathway can be seen in Table 5.

Table 5: List of Transition Times Used for the Plutonium Implosion-Type Weapon with Illicit Plutonium Purchase Proliferation Pathway Outside of the JCPOA. The days listed are the transition times used as reference times for each task. The testing of delivery systems and the production of untested weapons designs is 1 day in this case because they are known. The time required to construct testing facilities and to conduct weapons testing are taken from the Pakistani historic model.

Number	Transitions	Days
1	Purchas Pu Metal internationally	365
2	Retrofit for nuclear payload	60
3	Test Delivery/Missile Systems (existing)	1
4	Possess Deliverable Pu Weapon	1
5	Produce Pu Imp Explosive	180
6	Subcritical (cold) Test Pu Design with Natural Uranium	192
7	Nuclear Test Pu Nuclear Explosive	192
8	Prepare Pu Subcritical (cold) Testing Facility	4434
9	Prepare Pu Nuclear Explosive Testing Facility	2202
10	Design Pu Implosion Weapon (existing design)	1
11	Initiate Weapons R&D	1

5. PROLIFERATION PATHWAYS WITH THE JCPOA IN PLACE

Nine pathways were modeled using the requirements of the JCPOA as a starting point. Requirements of the JCPOA which effect proliferation include:

- Reduction in centrifuge capacity
- Reduction in SNM stockpile
- Arak HWRR retrofit to use LEU fuel
- Heavy water production strictly limited
- No spent fuel will remain in country
- Reprocessing R&D not permitted
- AVLIS R&D not permitted

Three different types of weapons were modeled within the simulations including: HEU gun-type weapon, HEU implosion-type weapon, and WGPu implosion-type weapon. The pathways modeled for gun-type weapons include:

1. Only allowed enrichment capacity
2. Additional covert enrichment facility
3. New AVLIS program; design and construction of facility modeled within the path
4. Existing AVLIS facility
5. Illicit purchase of 5000 kg of UF_6 enriched to 3.5%
6. Illicit purchase of 200 kg of UF_6 enriched to 20%

The plutonium pathways included the reprocessing of spent fuel as well as the illicit purchase of weapons-grade plutonium metal.

The gun-type weapon requires considerably less skill, knowledge, testing and expertise then compared with the requirements of an implosion-type weapon.[45] Because of this unidirectional sway, the modeling of the gun-type was always used to see the difference made by a specific pathway.

5.1 Gun-Type Weapon Using Allowed Enrichment Capacity

The material pathways necessary for a gun-type weapon include the mining, milling, conversion, and enrichment of uranium. The facility pathways involve the reconfiguration of the existing enrichment hall to facilitate the production of WGU, R&D of delivery systems, and the testing of gun-type weapon designs. The transitions times used for the entire proliferation pathway can be seen in Table 6.

Table 6: List of Transition Times Used for the Gun-Type Weapon Proliferation Pathway with Enrichment Allowed by the JCPOA. The days listed are the transition times used as reference times for each task. The days for material pathways (mining, milling, and conversion) are times for 1 kg of ^{235}U to pass through that stage. While enrichment times are inclusive for the material needed for the gun-type weapon. The construction of the enrichment and metal conversion facilities is 1 day in this case because they are existing. This is also the case for the testing of delivery systems and the production of untested weapons designs.

Number	Transitions	Days
1	Yellowcake from Gachin converted to UF6	1
2	Yellowcake from Ardakan converted into UF6	1
3	Produce yellowcake in Gachin mill	3
4	Mine Gachin	2

Table 6: Continued

Number	Transition	Days
5	Produce yellowcake in Ardakan Production plant	2
6	Convert U3O8 to UF6 for use in centrifuge facility	1
7	Mine Saghand	1
8	Operate downsized Natanz LEU Enrichment Facility	880
9	Build downsized Natanz enrichment facility (existing facility)	1
10	Operate Covert Natanz Centrifuge WGU Plant	242
11	Reconfigure downsized Natanz LEU Plant for WGU production	30
12	Operate HEU Metal Conversion Facility	84
13	Build U Metal Conversion Facility (existing facility)	1
14	Retrofit for nuclear payload	60
15	Test Delivery/Missile Systems (existing technology)	1
16	Possess Deliverable U Gun Weapon	1
17	Produce U Gun Explosive	180
18	Design U Gun Explosive (existing design)	1
19	Initiate Weapons R&D	1

5.2 Gun-Type Weapon Using Additional Enrichment Capacity

The material pathways necessary for a gun-type weapon in this pathway include the mining, milling, conversion, and enrichment of uranium. The facility pathways involve the reconfiguration of the enrichment hall to facilitate the production of WGU, the construction of an additional enrichment facility with approximately 14,000 SWU per year, R&D of delivery systems, and the testing of gun-type weapon designs. The time to build the additional enrichment facility is taken from the Pakistani historical case of Kahuta Enrichment Facility. The transitions times used for the entire proliferation pathway can be seen in Table 7.

Table 7: List of Transition Times Used for the Gun-Type Weapon Proliferation Pathway with Additional Enrichment Facility. The days listed are the transition times used as reference times for each task. The days for material pathways (mining, milling, and conversion) are times for 1 kg of ^{235}U to pass through that stage. While enrichment times are inclusive for the material needed for the gun-type weapon. The construction of the metal conversion facilities is 1 day in this case because it is existing. This is also the case for the testing of delivery systems and the production of untested weapons designs. The time used in the construction of the additional enrichment facility is from the Pakistan historical model of the Kahuta Enrichment Facility.

Number	Transitions	Days
1	Yellowcake from Gachin converted to UF6	1
2	Yellowcake from Ardakan converted into UF6	1
3	Produce yellowcake in Gachin mill	3
4	Mine Gachin	2
5	Produce yellowcake in Ardakan Production plant	2
6	Convert U3O8 to UF6 for use in centrifuge facility	1
7	Mine Saghand	1
8	Operate two LEU plants	213
9	Build additional enrichment facility	1825
10	Operate Covert WGU Plant	60
11	Reconfigure LEU Plant for WGU production	30
12	Operate HEU Metal Conversion Facility	84

Table 7: Continued

Number	Transition	Days
13	Build U Metal Conversion Facility (existing)	1
14	Retrofit for nuclear payload	60
15	Test Delivery/Missile Systems (existing technology)	1
16	Possess Deliverable U Gun Weapon	1
17	Produce U Gun Explosive	180
18	Design U Gun Explosive (existing design)	1
19	Initiate Weapons R&D	1

5.3 Gun-Type Weapon Utilizing a New AVLIS Enrichment Program

The material pathways necessary for a gun-type weapon in this pathway include the mining, milling, conversion, and enrichment of uranium. The facility pathways involve the reconfiguration of the enrichment hall to facilitate the production of WGU, the design and construction of an AVLIS enrichment facility, R&D of delivery systems, and the testing of gun-type weapon designs. The transitions times used for the entire proliferation pathway can be seen in Table 8.

5.4 Gun-Type Weapon Utilizing an Existing AVLIS Enrichment Program

The material pathways necessary for a gun-type weapon in this pathway include the mining, milling, conversion, and enrichment of uranium. The facility pathways involve the reconfiguration of the enrichment hall to facilitate the production of WGU, utilization of existing enrichment facilities (centrifuge and AVLIS), R&D of delivery systems, and the testing of gun-type weapon designs. The transitions times used for the entire proliferation pathway can be seen in Table 9.

Table 8: List of Transition Times Used for the Gun-Type Weapon Proliferation Pathway with a New AVLIS Enrichment Facility. The days listed are the transition times used as reference times for each task. The days for material pathways (mining, milling, and conversion) are times for 1 kg of ^{235}U to pass through that stage. While HEU enrichment times are inclusive for the material needed for the gun-type weapon. The construction of the metal conversion facility is 1 day in this case because it is existing. This is also the case for the testing of delivery systems and the production of untested weapons designs. The construction time for the AVLIS facility utilizes the Pakistani historical model of the construction of the New Labs facility.

Number	Transitions	Days
1	Yellowcake from Gachin converted to UF6	1
2	Yellowcake from Ardakan converted into UF6	1
3	Produce yellowcake in Gachin mill	3
4	Mine Gachin	2
5	Produce yellowcake in Ardakan Production plant	2
6	Convert U3O8 to UF6 for use in centrifuge facility	1
7	Mine Saghand	1
8	Build pilot AVLIS facility (existing facility)	0
9	Build full scale AVILS facility	1836
10	Operate AVLIS LEU plant	30
11	Build downsized enrichment facility (existing facility)	1
12	Operate Covert Natanz Centrifuge WGU Plant	126

Table 8: Continued

Number	Transition	Days
13	Reconfigure downsized Natanz LEU Plant for WGU production	30
14	Operate HEU Metal Conversion Facility	84
15	Build U Metal Conversion Facility (existing facility)	1
16	Retrofit for nuclear payload	60
17	Test Delivery/Missile Systems (existing technology)	1
18	Possess Deliverable U Gun Weapon	1
19	Produce U Gun Explosive	180
20	Design U Gun Explosive (existing design)	1
21	Initiate Weapons R&D	1

Table 9: List of Transition Times Used for the Gun-Type Weapon Proliferation Pathway with an Existing AVLIS Enrichment Facility. The days listed are the transition times used as reference times for each task. The days for material pathways (mining, milling, and conversion) are times for 1 kg of ^{235}U to pass through that stage. While HEU enrichment times are inclusive for the material needed for the gun-type weapon. The construction of the metal conversion facility, LEU enrichment facility, and AVLIS facility is 1 day in this case because they are existing. This is also the case for the testing of delivery systems and the production of untested weapons designs.

Number	Transitions	Days
1	Yellowcake from Gachin converted to UF6	1
2	Yellowcake from Ardakan converted into UF6	1
3	Produce yellowcake in Gachin mill	3
4	Mine Gachin	2
5	Produce yellowcake in Ardakan Production plant	2

Table 9: Continued

Number	Transition	Days
6	Convert U3O8 to UF6 for use in centrifuge facility	1
7	Mine Saghand	1
8	Build pilot AVLIS facility (existing facility)	1
9	Build full scale AVILS facility (existing facility)	1
10	Operate AVLIS LEU plant	30
11	Build downsized enrichment facility (existing)	1
12	Operate Covert Centrifuge WGU Plant	126
13	Reconfigure downsized Natanz LEU Plant for WGU production	30
14	Operate HEU Metal Conversion Facility	84
15	Build U Metal Conversion Facility (existing facility)	1
16	Retrofit for nuclear payload	60
17	Test Delivery/Missile Systems	180
18	Possess Deliverable U Gun Weapon	1
19	Produce U Gun Explosive	180
20	Design U Gun Explosive (existing design)	60
21	Initiate Weapons R&D	1

5.5 Gun-Type Weapon Using an Illicit Purchase of 5000 kg of UF_6 Enriched to 3.5%

The material pathways necessary for gun-type Weaponization includes the mining, milling, conversion, enrichment of uranium, and the purchase of 5000 kg of UF_6 which is enriched to 3.5%. The facility pathways involve the reconfiguration of the existing enrichment hall to facilitate the production of WGU, R&D of delivery systems, and the testing of gun-type weapon designs. The transitions times used for the entire proliferation pathway can be seen in Table 10.

5.6 Gun-Type Weapon Using an Illicit Purchase of 200 kg of UF_6 Enriched to 20%

The material pathways necessary for a gun-type weapon in this pathway include the mining, milling, conversion, enrichment of uranium, and the purchase of 200 kg of UF_6 which is enriched to 20%. The facility pathways involve the reconfiguration of the existing enrichment hall to facilitate the production of WGU, R&D of delivery systems, and the testing of gun-type weapon designs. The transitions times used for the entire proliferation pathway can be seen in Table 11.

5.7 HEU Implosion-Type Weaponization

The material pathways necessary for a HEU implosion weapon includes the mining, milling, conversion, and enrichment of uranium. The facility pathways involve the reconfiguration of the existing enrichment hall to facilitate the production of WGU, R&D of delivery systems, and the hot and cold testing of implosion weapon designs. The times used for hot and cold tests and test preparation is derived from the historical example of the Pakistani nuclear program.[7, 41] The transitions times used for the entire proliferation pathway can be seen in Table 12.

Table 10: List of Transition Times Used for the Gun-Type Weapon Proliferation Pathway Which Includes the Illicit Purchase of 5000 kg of UF_6 Enriched to 3.5%. The days listed are the transition times used as reference times for each task. The days for material pathways (mining, milling, and conversion) are times for 1 kg of ^{235}U to pass through that stage. While enrichment times are inclusive for the material needed for the gun-type weapon. The construction of the enrichment facility and metal conversion facility is 1 day in this case because it is existing. This is also the case for the testing of delivery systems and the production of untested weapons designs. The operation time for the LEU facility is 1 day because the enrichment level of the illicit material purchased is greater than this first enrichment step.

Number	Transitions	Days
1	Yellowcake from Gachin converted to UF6	1
2	Yellowcake from Ardakan converted into UF6	1
3	Produce yellowcake in Gachin mill	3
4	Mine Gachin	2
5	Produce yellowcake in Ardakan Production plant	2
6	Convert U3O8 to UF6 for use in centrifuge enrichment	1
7	Mine Saghand	1
8	Operate downsized LEU plant	1
9	Build downsized enrichment facility (existing facility)	1
10	Operate Centrifuge WGU Plant	340
11	Reconfigure downsized Natanz LEU Plant for WGU production	30
12	Operate HEU Metal Conversion Facility	84
13	Build U Metal Conversion Facility (existing facility)	1
14	Retrofit for nuclear payload	60
15	Test Delivery/Missile Systems (existing technology)	1
16	Possess Deliverable U Gun Weapon	1
17	Produce U Gun Explosive	180
18	Design U Gun Explosive (existing design)	1
19	Initiate Weapons R&D	1

Table 11: List of Transition Times Used for the Gun-Type Weapon Proliferation Pathway Which Includes the Illicit Purchase of 200 kg of UF6 Enriched to 20%. The days listed are the transition times used as reference times for each task. The days for material pathways (mining, milling, and conversion) are times for 1 kg of ^{235}U to pass through that stage. While enrichment times are inclusive for the material needed for the gun-type weapon. The construction of the enrichment facility and metal conversion facility is 1 day in this case because it is existing. This is also the case for the testing of delivery systems and the production of untested weapons designs. The operation time for the LEU facility is 1 day because the enrichment level of the illicit material purchased is greater than this first enrichment step.

Number	Transitions	Days
1	Yellowcake from Gachin converted to UF6	1
2	Yellowcake from Ardakan converted into UF6	1
3	Produce yellowcake in Gachin mill	3
4	Mine Gachin	2
5	Produce yellowcake in Ardakan Production plant	2
6	Convert U3O8 to UF6 for use in centrifuge enrichment	1
7	Mine Saghand	1
8	Operate downsized LEU plant	1
9	Build downsized enrichment facility (existing)	1
10	Operate Covert Centrifuge WGU Plant	117
11	Reconfigure downsized LEU Plant for WGU production	30
12	Operate HEU Metal Conversion Facility	84
13	Build U Metal Conversion Facility (existing facility)	1
14	Retrofit for nuclear payload	60
15	Test Delivery/Missile Systems	180
16	Possess Deliverable U Gun Weapon	1
17	Produce U Gun Explosive	60
18	Design U Gun Explosive (existing design)	1
19	Initiate Weapons R&D	1

Table 12: List of Transition Times Used for the HEU Implosion-Type Weapon Proliferation Pathway. The days listed are the transition times used as reference times for each task. The days for material pathways (mining, milling, and conversion) are times for 1 kg of ^{235}U to pass through that stage. While enrichment times are inclusive for the material needed for the HEU implosion-type weapon. The construction of the enrichment and metal conversion facilities is 1 day in this case because they are existing. This is also the case for the testing of delivery systems and the production of untested weapons designs. The time to build the testing facilities and conduct testing was extracted from the Pakistani historic model.

Number	Transitions	Days
1	Operate 2nd stage enrichment facilities	135
2	Operate downsized LEU plant	949
3	Build downsized enrichment facility (existing facility)	1
4	Operate Covert Centrifuge WGU Plant	32
5	Reconfigure downsized LEU Plant for WGU production	30
6	Operate HEU Metal Conversion Facility	84
7	Build U Metal Conversion Facility (existing facility)	1
8	Retrofit for nuclear payload	60
9	Test Delivery/Missile Systems (existing technology)	1
10	Possess Deliverable HEU Weapon	1
11	Produce HEU Imp Explosive	180
12	Subcritical (cold) Test HEU Design with Nat U	192
13	Nuclear Test HEU Nuclear Explosive	192
14	Prepare HEU Subcritical (cold) Testing Facility	4434
15	Prepare HEU Nuclear Explosive Testing Facility	2202
16	Design HEU Implosion Weapon (existing design)	1
17	Initiate Weapons R&D	1
18	Yellowcake from Gachin converted to UF6	1

Table 12: Continued

Number	Transitions	Days
19	Yellowcake from Ardakan converted into UF6	1
20	Produce yellowcake in Gachin mill	3
21	Mine Gachin	2
22	Produce yellowcake in Ardakan Production plant	2
23	Convert U3O8 to UF6 for use in centrifuge enrichment	1
24	Mine Saghand	1

5.8 Plutonium Implosion-Type Weaponization Produced Utilizing Reprocessing Pathway

The material pathways necessary for a plutonium implosion-type weapon include the mining, milling, conversion, fuel fabrication, irradiation of fuel, and spent fuel reprocessing. The facility pathways involve the construction of a HWR, a reprocessing facility, heavy-water production plant, R&D of delivery systems, and the hot and cold testing of implosion weapon designs. The times used for hot and cold tests, test preparation, construction time of the reactor, and construction of reprocessing plant are derived from the historical example of the Pakistani nuclear program.[7, 41] The transitions times used for the entire proliferation pathway can be seen in Table 13.

Table 13: List of Transition Times Used for the Pu Implosion-Type Weapon Reprocessing Proliferation Pathway with JCPOA in Force. The days listed are the transition times used as reference times for each task. The days for material pathways (mining, milling, and conversion) are times for 1 kg of ^{235}U to pass through that stage. The investigation of fuel needs for reactor is 1 day in this case because they are known. This is also the case for the testing of delivery systems and the production of untested weapons designs. The time required to build the reprocessing facility, the time to build the HWR, the time required to reprocess the fuel, to construct testing facilities, to conduct weapons testing, and to produce the heavy water needed for the reactor are taken from the Pakistani historic model.

Number	Transitions	Days
1	Retrofit for nuclear payload	60
2	Test Delivery/Missile Systems (existing technology)	1
3	Possess Deliverable Pu Weapon	1
4	Produce Pu Imp Explosive	180
5	Subcritical (cold) Test Pu Design with Nat U	192
6	Nuclear Test Pu Nuclear Explosive	192
7	Prepare Pu Subcritical (cold) Testing Facility	4434
8	Prepare Pu Nuclear Explosive Testing Facility	2202
9	Design Pu Implosion Weapon (existing design)	1
10	Initiate Weapons R&D	1
11	Build Reprocessing Facility	2555
12	Reprocess at facility	165
13	Cool Fuel	200
14	Operate HWR	365
15	Design and build Heavy-Water Production Facility	5110
16	Construct HW Reactor	4380
17	Investigate Needs for HW reactor completion	30
18	Operate Nat Metal Conversion Facility	90

Table 13: Continued

Number	Transitions	Days
19	Yellowcake converted into UO2 for natural uranium fuel	2
20	Yellowcake from Gachin converted to UF6 in Esfahan	1
21	Yellowcake from Ardakan converted into UF6 in Esfahan	1
22	Produce yellowcake in Gachin mill	3
23	Mine Gachin	2
24	Produce yellowcake in Ardakan Production plant	2
25	Mine Saghand	1
26	Possess fuel for heavy-water reactor	1
27	Operate Esfahan Fuel Fabrication Facility	180
28	Investigate Fuel Fabrication Facilities and options	1

5.9 Plutonium Implosion-Type Weaponization Produced with Illicit Plutonium Metal Purchase

There are no material pathways necessary for a plutonium implosion-type weapon built with acquired plutonium metal. The facility pathways involve the hot and cold testing of implosion weapon designs, purchase of the plutonium metal, and delivery systems. The times used for hot and cold tests and test preparation are derived from the historical example of the Pakistani nuclear program.[7, 41] The transitions times used for the entire proliferation pathway can be seen in Table 14.

Table 14: List of Transition Times Used for the Plutonium Implosion-Type Weapon Constructed with Illicitly Purchased Plutonium Proliferation Pathway with the JCPOA in Force. The days listed are the transition times used as reference times for each task. The testing of delivery systems and the production of untested weapons designs is 1 day in this case because they are known. The time required to construct testing facilities and to conduct weapons testing are taken from the Pakistani historic model.

Number	Transitions	Days
1	Purchas Pu Metal internationally	365
2	Retrofit for nuclear payload	60
3	Test Delivery/Missile Systems (existing technology)	1
4	Possess Deliverable Pu Weapon	1
5	Produce Pu Imp Explosive	180
6	Subcritical (cold) Test Pu Design with Nat U	192
7	Nuclear Test Pu Nuclear Explosive	192
8	Prepare Pu Subcritical (cold) Testing Facility	4434
9	Prepare Pu Nuclear Explosive Testing Facility	2202
10	Design Pu Implosion Weapon (existing design)	1
11	Initiate Weapons R&D	1

6. ANALYSIS OF RESULTS

The file which is the output of the Nuclear Weapons Latency Computational Tool lists the times for each path that has been determined by the simulation. These times include the mean, or expected value, the mean standard deviation, minimum, and the mode.[7, 8] These times are listed in Tables 15 and 16.

Table 15: Proliferation Times for Models Simulating Conditions before the Enactment of the JCPOA.

Simulation	Mean Time (days)	Standard Deviation	Minimum (days)	Mode (days)
Gun-Type Weaponization	255	32.24	172	251
HEU Hot Tested Implosion-Type Simulation	2,541	624.34	1,335	3,059
HEU Cold Tested Implosion-Type Simulation	2,557	630.15	1,390	1,541
Pu Hot Tested Implosion-Type Simulation / Reprocessing	3,243	514.12	2,078	2,621
Pu Cold Tested Implosion-Type Simulation / Reprocessing	3,257	538.76	2,519	5,720
Pu Hot Tested Implosion-Type Simulation/ Pu Metal Purchase	2,573	614.97	1,336	2,596
Pu Cold Tested Implosion-Type Simulation / Pu Metal Purchase	2,517	629.81	1,408	1,817

The results of the simulations which reflect the Nuclear Weapons Latency of Iran before the JCPOA was enacted are listed in Table 15. The gun-type weapon is the most technological simple and requires the least testing and facility improvements, so it is expected that this nuclear weapons latency time would be the least. Additionally, the large stockpile of LEU enriched SNM can be expeditiously enriched further to WGU for use in this gun-type weapon. The HEU implosion weapon has a nuclear weapons latency time of near 10 times that of the gun-type weapon, 2,541 days for hot tested and 2,557 for cold tested, which was anticipated because of the testing facilities which must be built and the testing that must be conducted, however, the time modeled for the hot test was expected to be higher than that of the cold test. The plutonium implosion weapon which is manufactured utilizing reprocessing results in a latency period of 3,243 days for a hot test, and 3,257 days for a cold tested weapon. This pathway requires the same specialized testing facilities as the HEU implosion weapon, the large increase in the latency time in this case is due to the construction of the reprocessing facilities, the fuel fabrication for the HWR, the completion of the Arak HWRR, the irradiation time, and the cooling time of the fuel before reprocessing. I expected to see a wider discrepancy between the nuclear weapons latency of the hot vs. the cold test and a greater latency time for the hot tested weapon. The pathway that simulated the illicit purchase of plutonium metal results in a nuclear weapons latency of 2,573 for a hot tested weapon and 2,517 for one which is cold tested. This pathway does not vary before or after the JCPOA and does not show the large drop in latency that might have been predicted because of the testing facilities that must be constructed and the testing that must be undertaken to produce an implosion-type weapon. The results of these simulations are generally as expected and gave a good basis for comparison to the latency times after the JCPOA comes into effect.

Table 16: Proliferation Times for Models Simulating Conditions after the Enactment of the JCPOA.

Simulation	Mean Time (days)	Standard Deviation	Minimum (days)	Mode (days)
Gun-Type Weaponization With No Additional Facilities	1,346	247.49	897	1,123
Gun-Type Weaponization With an Additional Enrichment Facility	542	70.52	362	493
Gun-Type Weaponization With New AVLIS Facility	2,140	533.38	1,168	1,716
Gun-Type Weaponization With Existing AVLIS Facility	363	48.68	237	376
Gun-Type Weaponization With Illicit Purchase of 5000 kg of UF_6 Enriched to 3.5%	555	105.14	338	648
Gun-Type Weaponization With Illicit Purchase of 200 kg of UF_6 Enriched to 20%	331	46.05	215	349

Table 16: Continued

Simulation	Mean Time (days)	Standard Deviation	Minimum (days)	Mode (days)
HEU Hot Tested Implosion-Type Simulation	2,870	420.36	1,710	2,821
HEU Cold Tested Implosion-Type Simulation	2,878	441.52	1,787	2,496
Pu Hot Tested Implosion-Type Simulation / Reprocessing	4,711	1180.96	2,575	3,117
Pu Cold Tested Implosion-Type Simulation / Reprocessing	4,633	1132.08	2,488	6,523
Pu Hot Tested Implosion-Type Simulation/ Pu Metal Purchase	2,573	614.97	1,336	2,596
Pu Cold Tested Implosion-Type Simulation / Pu Metal Purchase	2,517	629.81	1,408	1,817

The results of the simulations that modeled proliferation pathways after the JCPOA is enacted are listed in Table 16. The nuclear weapon latency of a gun-type weapon with no additional facilities was 1,346 days. This was an expected increase since both the enrichment facilities and the stockpile had been greatly reduced by the JCPOA. When an additional enrichment facility with a 14,000 SWU was modeled, the latency drops, as expected to closer to the time seen before the JCPOA, however, the impact of the reduction of the SNM stockpile keeps the nuclear weapons latency higher.

The nuclear weapons latency of a model with a new AVLIS facility is high, 2,140 days. This is due to the construction time of the facility. When a path is modeled that contains an existing AVLIS facility the nuclear weapons latency dropped to 363 days. This is less than the nuclear weapons latency time seen with an additional gaseous centrifuge facility because of the reduction in the enrichment times and lack of construction times.

The production of SNM represents the majority of time and energy needed to produce a weapon. The purchase of SNM bypasses this timely path and simulates a stockpile of enriched material, because the JCPOA called for such a dramatic reduction of Iran's stockpile this pathway will illustrate the effects of this reduction. The pathway which modeled the illicit purchases of 5,000 kg of UF_6 enriched to 3.5% has a nuclear weapons latency of 555 days and the illicit purchases of 200 kg of UF_6 enriched to 20% has a nuclear weapons latency of 331 days. Since the majority of energy is expended during the first stages of enrichment it was expected that the latency would drop as the enrichment of the illicitly purchased material rose.

A HEU implosion-type weapon requires less enriched uranium than a gun-type weapon, but the facilities needed for the production and testing of implosion-type weapons are specialized and must be constructed. Therefore, it was expected the nuclear weapons latency for an implosion-type weapon would be longer than for a gun-type weapon. The plutonium weapon requires fuel fabrication, irradiation, and reprocessing prior to any testing and was consequently expected to have a higher nuclear weapons latency.

A determination of the nuclear weapons latency value of the JCPOA for each model is seen in Table 17. The gun-type weapon pathway with only with the facilities allowed under the JCPOA shows a latency of 1,346 days. This time is a 428% increase when compared to the to the 255 latency period which was seen in the simulations before the JCPOA. Since the enrichment capabilities were reduced to 17% of their previous size and the SNM stockpile reduced, this is the level of increase that was expected.

When an additional IR-1 enrichment facility, similar in size to Natanz, was added to the gun-type weapon pathway the latency dropped to 542 days, which is still more than double the latency prior to the JCPOA. The difference is caused by the loss of the second enrichment facility, the use of the IR-2m centrifuges, and the absence of the large stockpile of SNM which existed prior to the JCPOA. The large footprint and energy consumption of a facility such as this makes it risky to operate, especially when under Additional Protocols; the Natanz Facility was built and operated as a covert facility, but was discovered even without the Additional Protocols in place.

The gun-type pathways that model an LEU AVLIS enrichment facility include a path utilizing an existing facility and a path where the facility must be constructed. The path involving the building of this facility has a latency of 2,140 days and the path with an existing facility has a latency of 363 days. The difference here is obviously the design and building time of the facility, but these latency times illustrate that an existing AVLIS facility shows a drastically reduced latency, but still greater than the latency prior to the JCPOA because of the smaller SNM stockpile. An AVLIS facility has a small footprint and energy signature, which would make it more easily concealed under IAEA inspections and Additional Protocols. These factors make AVLIS an enormous proliferation concern.

Table 17: Nuclear Weapons Latency Value of the JCPOA with Associated Uncertainties.

Weapon Type	Mean Time Before JCPOA (days)	Simulation with JCPOA in Force	Mean Time After JCPOA (days)	Value of the JPCOA (days)	Uncertainty (days)
Gun-Type	255 ± 32	No Additional Facilities	1,346 ± 247	1092	249
		Additional Enrichment Facility	542 ± 71	287	78
		New AVLIS Facility	2,140 ± 533	1886	534
		Existing AVLIS Facility	363 ± 49	109	59
		Illicit Purchase of 5000 kg of 3.5% Enriched UF_6	555 ± 105	301	110
		Illicit Purchase of 200 kg of UF_6 Enriched to 20%	331 ± 46	76	56
HEU Implosion-Type	2,541 ± 624	Hot Tested	2,870 ± 420	382	752
	2,557 ± 630	Cold Tested	2,878 ± 442	322	770
Pu Implosion-Type	3,243 ± 1255	Hot Tested Reprocessing	4,711 ± 1241	1468	1765
	3,257 ± 1311	Cold Tested Reprocessing	4,633 ± 1189	1376	1770
	2,573 ± 615	Hot Tested Illicit Pu Metal Purchase	2,573 ± 615	-	-
	2,517 ± 630	Cold Tested Illicit Pu Metal Purchase	2,517 ± 630	-	-

The next two pathways involve the purchase of enriched UF_6 to use in the production of a gun-type weapon. The first involves the purchase of 5,000 kg of UF_6 enriched to 3.5% and the weapons latency in this case is 554 days. The second is the purchase of 200 kg of UF_6 which is enriched to 20% and the latency is 331 days. The energy needed to enrich uranium from natural to weapons-grade decreases exponentially as the enrichment increases. The enrichment from natural to 3.5% requires approximately 148 SWU/kg; the enrichment from 3.5% to 20% requires approximately 42 SWU/kg; while the enrichment from 20% to 93% requires only approximately 20 SWU/kg.[45] This pathway eliminates the lower enrichment stages, which are also the more time consuming and energy greedy stages, resulting in the shortened latency. The purchase of 20% enriched material has a latency which is closest to the latency prior to the JCPOA. This purchase represents an amount that is greater than the SNM stockpile prior to the JCPOA and if greater enrichment facilities existed at the time of this purchase the latency might be less than before the JCPOA.

The HEU implosion pathway is less dependent on material production than a gun-type weapon, because of the reduced demand of WGU, but more reliant on the constructing of testing facilities and conducting tests. Therefore, the pathways show relatively the same latency before and after the enactment of the JCPOA. The slight increase seen in the latency as a result of the JCPOA, 2,541 days to 2,870 days for the hot test option and 2,557 to 2,878 for the cold test option, are because of the difference in the enrichment capability and in the stockpile of SNM.

The Pu implosion pathway after the JCPOA requires the construction of a HWR, a heavy-water production facility, a reprocessing facility, and the fabrication of fuel. The activities that lengthen this time from before and after the JCPOA include the complete construction of a reactor instead of only the completion of Arak HWR, and the construction of a heavy-water production facility instead of the time needed to produce enough heavy water in an existing facility. The hot test option shows an increase from 3,243 days to 4,711 days while the cold test option changes from 3,257 days to 4,633 days.

7. CONCLUSION

In this work we have calculated our best estimate of the Nuclear Weapons Latency for Iran both with and without the JCPOA in force. Based on these results, we expect that the JCPOA will lengthen Iran's Nuclear Weapons Latency. This expected value assumes application of stringent inspections and the requirements of the Additional Protocols. The establishment of an AVLIS facility and the purchase of 20% enriched UF_6 cause the most concern in these simulation. This is as expected, since the reduction of enrichment capabilities have been shown to have the most impact, increasing the latency of all types of weapons.

The illicit purchase of 20% enriched UF_6 drops the latency to almost pre-JCPOA values. This purchase would dramatically shorten the material pathways and allow the Iranians to circumvent the most limiting factors in the agreement and move forward with their weapons testing and production. This purchase would be a short term advance, since the repeated acquisition of this material would be unlikely and result in only enough material for a single gun-type weapon making the Iranians more of a target than a nuclear power.

A more troubling advancement than the illicit purchase of 20% enriched uranium would be in the field of AVLIS. The acquisition of AVLIS technology by Iran would be a significant leap forward in their weapons program, especially considering that the facility modeled was a LEU facility. If Iran were to inaugurate a HEU AVLIS facility, the nuclear weapons latency would certainly be greatly lessened. The AVLIS is, however, a complicated and exacting task which has not been mastered by leading researcher in the field. Since this level of expertise takes time, money, and specialized equipment, the chance of success of a covert HEU AVLIS facility is low, and lessened more if inspections and import restrictions are continually enforced. To combat against AVLIS testing the level of the SNM stockpile should be closely monitored. Diversion of this material would be necessary to facilitate testing.

In conclusion, the Iranian path toward a weapon has clearly been hindered by the JCPOA, the extent of which depends upon the path taken to a weapon and the amount of external assistance utilized. Iran as a nuclear weapon state would likely result in regional instability and could have many consequences, such as an nuclear arms race with Saudi Arabia, and military action by either the United States or Israel. This agreement hopes to improve Iran's regional and international dialogue, ending the sanctions and isolation that Iran, and the Iranian people, have suffered under for years. This opening up of Iran to more soft power influences, by the United States and other moderate and progressive nations, while hindering the forward progress of the nuclear weapon production could be the most lasting and effective outcome of the JCPOA.

REFERENCES

1. State, U.S.D.o. *Joint Comprehensive Plan of Action*. 2015 [cited 2015 November 22]; Available from: http://www.state.gov/e/eb/tfs/spi/iran/jcpoa/

2. Kaplow, J.M. and R.D. Gibbons, *The days after a deal with Iran*. Perspective: PE-135-RC. 2015: [Santa Monica, California] : Rand Corporation, [2015].

3. Doyle, J., *Nuclear safeguards, security and nonproliferation : achieving security with technology and policy*. 2008: Amsterdam ; Boston : Butterworth-Heinemann, [2008].

4. Mozley, R.F., *The politics and technology of nuclear proliferation*. 1998: Seattle : University of Washington Press, [1998].

5. Nikou, S., *Timeline of Iran's Nuclear Activities | The Iran Primer*. 2016.

6. Mark, J.C., F. von Hippel, and E. Lyman, *Explosive properties of reactor-grade plutonium.* Science and Global Security, 2009. **17**(2-3): p. 170-185.

7. Sweeney, D.J., *Nuclear Weapons Latency*. 2014.

8. Sweeney, D.J., *Nuclear Weapons Latency Tool Manual and Operation*, M. Johansen, Editor. 2015.

9. *Uranium Mine Ownership - Asia*. [cited 2015 November 28]; Available from: http://www.wise-uranium.org/uoasi.html#IR.

10. *Bandar Abbas Uranium Production Plant (BUP) | NTI*. [cited 2015 December 3]; Available from: http://www.nti.org/facilities/155/.

11. *World Nuclear Association - Nuclear Power in Iran*. [cited 2015 December 1]; Available from: http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/iran.aspx.

12. *World Nuclear Association - Uranium Mining Overview*. 2015 [cited 2015 December 20]; Available from: http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview.aspx.

13. *Uranium Mining - Nuclear Sites - ISIS NuclearIran*. [cited 2015 November 27]; Available from: http://www.isisnucleariran.org/sites/detail/uranium-mining/.

14. *Esfahan - Nuclear SitesISIS NuclearIran*. [cited 2015 December 15]; Available from: http://www.isisnucleariran.org/sites/esfahan/.

15. Migliorini, P., et al., *Iranian Breakout Estimates, Updated September 2013*. 2013, Institute for Science and International Security.

16. *Natanz - Nuclear Sites - ISIS NuclearIran*. [cited 2015 November 22]; Available from: http://www.isisnucleariran.org/sites/detail/natanz/.

17. Albright, D. and C. Walrond, *Iran's Advanced Centrifuges | Institute for Science and International Security*. 2011.

18. Agency, D.G.o.t.I.A.E., *Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran*. 2013, International Atomic Energy Agency.

19. *Fordow Fuel Enrichment Plant (FFEP) - Nuclear Sites - ISIS NuclearIran*. [cited 2015 November 26]; Available from: http://www.isisnucleariran.org/sites/detail/fordow/.

20. *Lashkar Ab'ad â□ " Laser enrichment - Nuclear Sites - ISIS NuclearIran*. [cited 2015 December 1]; Available from: http://www.isisnucleariran.org/sites/detail/lashkar-abad-laser-enrichment/.

21. Cordesman, A.H. and K.R. Al-Rodhan, *Iran's weapons of mass destruction : the real and potential threat*. Significant issues series: v. 28, no. 3. 2006: Washington, D.C. : Center for Strategic and International Studies, [2006].

22. Krause, J., *Iran's nuclear programme : strategic implications*. Routledge global security studies. 2012: London ; New York : Routledge, 2012.

23. *Arak Nuclear Complex | NTI*. [cited 2015 November 20]; Available from: http://www.nti.org/facilities/177/.

24. *Arak Complex - Nuclear Sites - ISIS NuclearIran*. [cited 2015 December 1]; Available from: http://www.isisnucleariran.org/sites/detail/arak/.

25. *Bushehr Nuclear Power Plant - Nuclear Sites - ISIS NuclearIran*. [cited 2015 November 22]; Available from: http://www.isisnucleariran.org/sites/detail/bushehr/.

26. *Bushehr Nuclear Power Plant (BNPP) | NTI*. 2013 [cited 2015 December 1]; Available from: http://www.nti.org/facilities/184/.

27. Inskeep, S., *Born In the USA: How America Created Iran's Nuclear Program*. 2015: NPR. p. 49:47.

28. *Tehran Nuclear Research Center - Nuclear Sites - ISIS NuclearIran*. [cited 2015 November 25]; Available from: http://www.isisnucleariran.org/sites/detail/tehran/.

29. *Uranium Conversion and Fuel Fabrication - Nuclear Sites - ISIS NuclearIran*. [cited 2015 November 20]; Available from: http://www.isisnucleariran.org/sites/by-type/category/uranium-conversion-and-fuel-fabrication/.

30. *Fuel Fabrication Laboratory (FFL) | NTI*. [cited 2015 November 20]; Available from: http://www.nti.org/facilities/160/.

31. *Fuel Manufacturing Plant (FMP) | NTI*. [cited 2015 November 20]; Available from: http://www.nti.org/facilities/161/.

32. *Zirconium Production Plant (ZPP) | NTI*. [cited 2015 November 20]; Available from: http://www.nti.org/facilities/162/.

33. Tsoulfanidis, N., *The nuclear fuel cycle*. 2013: La Grange Park, Illinois : American Nuclear Society, [2013] [3rd edition].

34. *Weaponization-Related R&D - Nuclear Sites - ISIS NuclearIran*. [cited 2015 December 27]; Available from: http://www.isisnucleariran.org/sites/by-type/category/weaponization-related-rd/.

35. *Tehran Nuclear Research Center (TNRC) | NTI*. [cited 2015 November 22]; Available from: http://www.nti.org/facilities/265/.

36. *Physics Research Center (PHRC) | NTI*. [cited 2015 December 27]; Available from: http://www.nti.org/facilities/263/.

37. *Parchin - Nuclear Sites - ISIS NuclearIran*. [cited 2015 November 23]; Available from: http://www.isisnucleariran.org/sites/detail/parchin/.

38. *Parchin Military Complex | NTI*. [cited 2015 December 27]; Available from: http://www.nti.org/facilities/264/.

39. *Jabr Ibn Hayan Mulitpurpose Laboratories (JHL) | NTI*. [cited 2015 December 1]; Available from: http://www.nti.org/facilities/157/.

40. *Population, total | Data | Table*. 2015; Available from: http://data.worldbank.org/indicator/SP.POP.TOTL.

41. Khan, F.H., *Eating grass : the making of the Pakistani bomb*. 2012: Stanford, California : Stanford Security Studies, Stanford University Press, [2012].

42. Agency, I.A.E., *PRIS - Reactor Details.* 2015.

43. *Unclassified Report on Military Power of Iran*, C.D. Action, Editor. p. 11.

44. *Profile for Iran | NTI.* 2015. **2015**.

45. Council, C.o.I.S.a.A.C.P.a.G.A.N.R., *Monitoring Nuclear Weapons and Nuclear-Explosive Materials: An Assessment of Methods and Capabilities*. 2005, Washington, DC: The National Academies Press.